Time course differences between bilinguals and monolinguals in the Simon task

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Abstract

In the Simon task, individuals need to indicate the color of the target stimulus while ignoring its spatial location. The Simon Effect refers to the finding that participants respond more quickly when the target stimulus and response effector are spatially compatible compared to when they are not. Thus, to optimize performance in the Simon task, individuals need to ignore the task-irrelevant (spatial) information and attend to the task-relevant (color) information. Interestingly, it has been reported that bilinguals are faster than monolinguals in the Simon task and that they exhibit a smaller Simon effect. The present study investigates whether this so-called bilingual advantage is due to bilinguals being better at ignoring task-irrelevant information, or better at activating task-relevant information, or both. In a button-press version of the task, we do not observe a bilingual advantage, but in a reach-to-touch paradigm, we find that bilinguals suppress task-irrelevant information for longer and activate task-relevant information sooner.

Keywords Simon task, reaching paradigm, bilingual advantage, relevant information, irrelevant information

Introduction

In the Simon task, the responses are more accurate and faster on congruent trials, in which the stimulus location and response key are on the same side (e.g., red color square, presented on the left side of the fixation, requiring a left-hand response). In contrast, responses are less accurate and slower on incongruent trials, in which the stimulus location and response key are on the opposite sides (e.g., red color square presented on right side of the fixation, requiring a left-hand response). The response time difference between the congruent and incongruent trials is known as the Simon effect (Hedge & Marsh, 1975), and is well accounted for by dual route theories (Kornblum, Hasbroucq, & Osman, 1990; De Jong, Liang & Lauber, 1994; Ridderinkhof, 2002; Wascher, Schatz, Kuder, & Verleger, 2001; Lu & Proctor, 1995). According to these theories, a fast direct route of response selection is thought to activate responses that spatially correspond to the stimulus location attribute. Activation produced along this direct route is thought to dissipate rapidly over time. Additionally, a slow indirect route is proposed to activate responses on the basis of the task-relevant stimulus color attribute. Activation produced along this route is thought to proceed more slowly than the direct route. The aim of the present study was to use the dual route accounts of the Simon effect to guide a systematic investigation of where, if at all, differences between monolinguals and bilinguals exist in the Simon task. Are group differences present in the dynamics of activating task-relevant information or are group differences present in the dynamics of ignoring task-irrelevant information? We investigated this question across two experiments. In the first experiment we used a mathematical modelling approach of reaction time data and in the second experiment we used a reach-to-touch paradigm.

The Simon task is the most commonly used non-linguistic response conflict task in bilingual cognitive advantage studies (e.g., Bialystok, Craik, Klein, & Viswanathan, 2004; Bialystok, Martin, & Viswanathan, 2005; for a review see Hilchey & Klein, 2011; Bialystok, 2009). In this literature, there is ample evidence of a bilingual cognitive advantage in children, middle-aged and old-aged adults for the Simon task (e.g., Bialystok et al., 2004; Bialystok, Martin, & Viswanathan, 2005; Martin-Rhee & Bialystok, 2008; Salvatierra & Rosselli, 2010; Bialystok, Craik, & Luk, 2012; Schroeder & Marian, 2012; Poarch & van Hell, 2012). However, in young adults a bilingual cognitive advantage is quite elusive in the Simon task (e.g., Bialystok, Martin & Viswanathan, 2005; Bialystok, Craik, Grady, Chau, Ishii, Gunji & Pantev, 2005; Bialystok, 2006; Salvatierra & Rosselli, 2010; Kousaie & Phillips, 2012; Gathercole, Thomas, Kennedy et al., 2014; Paap, Johnson, & Sawi, 2014). For example, Bialystok and colleagues investigated cognitive control differences between monolinguals and bilinguals across children, young adults and elderly adults using the Simon task (Bialystok, Martin, & Viswanathan, 2005). Their results suggested faster reaction time and smaller magnitude of Simon effect only in bilingual children and elderly adults. Similar behavioural performance between bilingual and monolingual young adults was attributed to peak age of cognitive functioning (Bialystok, Martin, & Viswanathan, 2005; Salvatierra & Rosselli, 2010; Hilchey & Klien, 2011; Bialystok, Craik, & Luk, 2012). These results were consistent even on varying different participant and experimental factors such as the type of bilingualism (early bilinguals: Bialystok, Martin, & Viswanathan, 2005; late bilinguals: Salvatierra & Rosselli, 2010), bilingual language sample (Bialystok, Martin, & Viswanathan, 2005; Salvatierra & Rosselli, 2010; Kousaie & Phillips, 2012; Gathercole, Thomas, Kennedy et al., 2014; Paap, Johnson, & Sawi, 2014), experimental task load (Bialystok, 2006; Salvatierra & Rosselli, 2010), and block design (only congruent and incongruent trials: Bialystok, Martin, & Viswanathan, 2005; Bialystok et al., 2005; Bialystok, 2006; Salvatierra & Rosselli, 2010; Paap, Johnson, & Sawi, 2014; all congruent, incongruent and neutral trials: Kousaie & Phillips, 2012). However, this was not the case in other non-linguistic conflict tasks, in which bilingual young adults outperformed monolinguals in the attentional network task (Costa, Hernandez, & Sebastian-Galles, 2008; Costa, Hernandez, Costa-Faidella, & Sebastian-Galles, 2009; Pelham & Abrams, 2014), the spatial Stroop task (Bialystok, 2006; Bialystok & DePape, 2009; Blumenfeld & Marian, 2014), the Stroop task (Bialystok, Craik, & Luk, 2008; Hernández, Costa, Fuentes, Vivas, & Sebastián-Gallès 2010; Coderre & van Heuven, 2014; Yow & Li, 2015), the lateralised attentional network task (Tao, Marzecova, Taft, Asanowicz, & Wodniecka, 2011; Marzecová, Asanowicz, Krivá, & Wodniecka, 2013), and task switching (Prior & Gollan, 2011; Prior & MacWhinney, 2010; Wiseheart, Viswanathan, & Bialystok, 2014). Overall, the contrasting findings across different tasks may also be due to the differences in the source of interference between stimulus-response information within each task (Miyake & Friedman, 2012).

Interestingly, there have been a handful of studies that have failed to detect a bilingual advantage in their behavioural measure even while detecting a group difference in physiological measures such as magneto-encephalography (MEG), and event related potentials (ERP) (cf. Bialystok et al. 2005; Kousaie & Phillips, 2012). For example, Bialystok et al. (2005) used MEG to investigate the neural correlates of the cognitive control mechanism in the Simon task in young adults. They correlated behavioural performance (response latencies) with brain activity and found in bilingual young adults that faster response latencies correlated with increased brain activation in the right superior and middle temporal, left superior and inferior frontal and cingulate regions. This same correlation in monolinguals was noted only in the left middle frontal regions. The authors speculated that the brain areas activated during the Simon task in bilinguals were similar to the brain areas that subserve language selection in bilingual speech production (Abutalebi & Green, 2007; Luk, Anderson, Craik, Grady, & Bialystok, 2010; Bialystok et al., 2005). Recently, Kousaie & Phillips (2012) examined the possibility of a bilingual cognitive advantage using ERPs in Stroop, Simon and Flanker tasks. The amplitude and latencies of N2 (said to be related to conflict detection and monitoring), P3 (said to be related to stimulus categorization time and resource allocation) and error related negativity (ERN) components were compared between groups. They did not observe any group differences in the behavioural measures but did in the ERP data. Specifically, the ERP data revealed processing differences between bilinguals and monolinguals in conflict monitoring (N2) and error detection (ERN) for Stroop task, in resource allocation (P3 amplitude) for Simon task and; in stimulus categorization (P3 latency) and error detection (ERN) for Flanker task. The ERP data demonstrated that bilinguals and monolinguals use different processes as a function of conflict tasks. To summarize, these studies present a puzzle insofar as bilinguals and monolinguals appear to recruit different brain areas to resolve conflict in the Simon and Stroop tasks even while achieving similar levels of performance.

To date, behavioural studies have largely used accuracy and reaction time data (from button press measures) separately to investigate the possibility of a bilingual advantage in the Simon task. However, the complex association between the accuracy and reaction time data in bilinguals and monolinguals decision processing remains unexplored. In the present study we incorporate an evidence-accumulation model of two choice reaction time tasks, in particular linear–ballistic accumulator model (LBA; Brown & Heathcote, 2008), to investigate the decision processing mechanism between bilingual and monolingual participants. The evidence accumulation model uses both response choice and time taken to complete a response choice, to reveal the dynamics of decision processing (e.g., Brown & Heathcote, 2005; 2008; Ratcliff & Rouder, 1998; Donkin, Brown, & Heathcote, 2011). The decision for a choice response is made when the accumulation of information (evidence) reaches its response threshold over time. There is a long history of simultaneously fitting both response latency and accuracy data to evidence accumulation models in cognitive psychology to reveal the decision processing mechanism (e.g., Brown & Heathcote, 2005; 2008; Ratcliff & Rouder, 1998; Donkin, Brown, & Heathcote, 2011). Previous researchers have employed modelling approach to capture the underlying decision making differences between elderly and young adults (Ratcliff, Thapar, & McKoon, 2001; 2003), children with ADHD and without ADHD (Kralunas & Huang-Pollock, 2013), high working memory and fluid intelligence young adults (Schmiedek, Oberauer, Wilhelm, Süβ, & Wittmann, 2007), when the mean reaction time and accuracy data alone failed to capture subtle group differences (Donkin, Averell, Brown, & Heathcote, 2009).

In our first experiment, we compared bilingual and monolingual young adults' accuracy and reaction time data by fitting them to the LBA model (Brown & Heathcote, 2008). This was done to provide further insight into how (if at all) the two groups differed in terms of evidence accumulation for overt responses using a modelling approach. The LBA model is the simplest evidence accumulation model applied to two choice reaction time experiments that estimates parameters (drift rate and response threshold) from the accuracy and reaction time data simultaneously (Brown & Heathcote, 2008; Donkin, Averell, Brown, & Heathcote, 2008). The parameter drift rate (v) is the rate at which evidence for a particular response is accumulated. The drift rate varies relative to the accumulator (True vs. False) and it indicates the quality of the stimulus. For example, in Figure 1 the drift rate on true accumulator (vT) indicates faster accumulation of evidence (information) and overt response choice than the drift on false accumulator. On the other hand, the response threshold (b) is the amount of evidence required before making a response. For example, a lower response threshold value produces a less cautious response and an increased response threshold value indicates more cautious response (see Fig.1).

Experiment 1: Modelling button press latencies

In our first experiment, participants indicated the color of a peripherally presented square by pressing an appropriate button as quickly and as accurately as they could. The purpose of this initial experiment was to fit the response latency and accuracy data to the LBA model to see if the modelling approach might reveal any differences between bilinguals and monolinguals that straight RTs have failed to reveal with young adults. To anticipate our results, we find a very strong Simon effect but do not find any differences between the two groups.

Method

Participants

A total of 40 participants were recruited from the Macquarie University participant pool. All participants completed a Language Experience and Proficiency Questionnaire (LEAP-Q; Marian, Blumenfeld, & Kaushankaya, 2007), and Edinburgh Handedness Inventory (Oldfield, 1971) before participating in the experiment. From this preliminary interview, the participants were assigned to either the bilingual group (N=20, mean age = 20.65 years, SD = 3.5; 15 females) or the monolingual group (N=20, mean age = 21.20 years, SD = 4.78; 14 females). For each of the languages they mentioned in the questionnaire, participants specified their age of acquisition, amount of language usage on daily basis, and proficiency rating in speaking, listening, and reading (on a 10-point rating scale from *0 = None* to *10 = Perfect*).

The demographic information of bilinguals and monolinguals are reported in Table 1. The two groups were matched in terms of age, years of formal education, handedness, non-verbal intelligence, video game playing, and parental education level. The handedness of participants was established using an Edinburgh Handedness Inventory (Oldfield, 1971) questionnaire. The average cumulative scores were calculated for each participant and only participants scoring above 40 were included for the study (right handed). In order to match for non-verbal intelligence across the groups, participants completed a shortened version of Raven's Advanced Progressive Matrices Set I (Raven, Raven, & Court, 1998). One point was given for each correct answer, with a maximum total of 12. Parental education level, determined as the average of the two parent's highest education level on a five-point scale (1= *did not graduate from high school*; 5=*earned a graduate or professional degree*) provided further information about socioeconomic background.

The bilingual speakers were heterogeneous language sample with a variety of other languages including Chinese (n=9), Hindi (n=3), Bengali (n=2), Arabic (n=2), and one speaker each of Serbian, Armenian, Sinhalese and Tagalog. Bilingual participants had been exposed to both English and their other language before the age of six, started actively using second language from the mean age of 4.84 years and 8 participants had immigrated to Australia (average years of stay: 5.12 years). None of the participants were left handed, had a history of speech, language, hearing deficits or any other neurological deficits. Ethical approval was obtained from the Macquarie University Human Research Ethics Committee.

Informed consent was obtained from participants at the beginning of the testing session and they were compensated financially or with course credit at the end of the each session.

Test Materials

Participants completed the general background questionnaire, Raven's Advanced Progressive Matrices Set 1 (Ravens et al., 1998), and the Simon task. In the general background questionnaire, they filled out their education history, parental education, history of computer usage, personal and family language history. Participants then completed the button press and reach-to-touch versions of Simon task in two different sessions. This was counterbalanced across participants in each group. In each session, they were seated at a viewing distance of about 90cm from the 23″ LED monitor (with 1920 x 1080 x 32 pixels at 120Hz) in a dimly lit room. Presentation® software from Neurobehavioral Systems (version 16.1) was used to deliver the stimulus. The stimuli consisted of red and green color squares of 50 mm sq. presented at 3^0 from the central fixation point in one of four locations on monitor (left, right, up, down). Participants were instructed to respond to the color of the target stimulus, irrespective of its location.

There were three different trial types (congruent trial, incongruent trial and neutral trial). The combination of target location and the corresponding response decided the type of trial. In congruent trial type (25% of the trials), the target was presented on the same side of the screen as its associated response key (e.g., red color square, presented on the left side of the fixation, requiring left button press response/reaching towards left response panel); whereas in the incongruent trial type (25% of the trials), stimulus location and its associated response key were on the opposite sides (e.g., red color square presented on right side of the fixation, requiring left button press response/reaching towards left response panel). In neutral trial type (50% of the trials), the stimulus location did not correspond to any response key (e.g., red color square, presented on either top/bottom side of the fixation, requiring left button press response/reaching towards left response panel).

Procedure

In button press version of the Simon task, half of the participants within each group were instructed to press the left button with the left index finger when they saw a red square and the right button with the right index finger when they saw a green square. The opposite response mapping was given to the remaining participants. Each trial began with a fixation cross for 500ms followed by three beeps at 500ms, 900ms, and 1200ms and the participants were asked to respond as quickly as they could following the third beep. The target stimulus appeared for 300ms in one of the four locations (left, right, up, down). The experiment began with a block of practice trials (n=40) followed by ten blocks of experimental trials (n=400). The entire task lasted approximately for 45min.

Results

The dependent measures were mean accuracy rate (%) and mean reaction time (ms). To test our hypothesis, we performed 3 x 2 ANOVA on accuracy (Table 2) and reaction time (Table 3) separately, with trial type (congruent, incongruent and neutral) as a within-participant factor and group (bilingual and monolingual) as a between participant factor.

Accuracy (%). The ANOVA analysis revealed a significant main effect of trial type, F (2, 76) = 43.91, $p < 0.001$, $\eta_p^2 = 0.32$. Further, we carried out pairwise t-tests with Bonferroni correction in order to investigate the main effect of trial type. The results revealed that participants were more accurate on congruent trials (M = 96.63, SD = 2.97) than neutral trials (M = 95.10, SD = 3.38; t = 2.68, $p < 0.05$) and incongruent trials (M = 88.30, SD = 8.02; t = 6.81, $p < 0.001$). And also participants' responses were more accurate on neutral trials than incongruent trials (t = 7.16, $p < 0.001$). There was no significant main effect of group, F (1, 38) = 1.12, $p = 0.29$, $\eta_p^2 = 0.01$; nor interaction between group and trial type, F (2, 76) = 1.51, $p = 0.22$, $\eta_p^2 = 0.01$, indicating no difference between bilinguals and monolinguals.

Reaction time (ms). Trials in which responses were too fast (less than 100ms) or too slow (greater than 1000ms) were excluded from analyses (resulting in 7.03% of the trials removed) (Proctor, Yamaguchi, & Vu, 2007). The ANOVA results revealed a significant main effect of trial type, F (2, 76) = 169.8, $p < 0.001$, $\eta_p^2 = 0.06$. Pairwise comparisons with Bonferroni corrected p values demonstrated that the participants were significantly faster on congruent trials (M = 503.23ms, SD = 112.53) than neutral trials (M = 523.54ms, SD = 106.12; t = 9.17, $p < 0.001$) and incongruent trials (M = 550.71ms, SD = 110.04; t = 16.59, $p < 0.001$). Further, the reaction time was also faster on neutral trials than incongruent trials (t = 10.33, $p < 0.001$). There was no significant main effect of group, F (1, 38) = 0.006, $p = 0.93$, $\eta_p^2 = 0.00$ and no interaction between group and trial type, F (2, 76) = 0.991, $p = 0.37$, $\eta_p^2 = 0.00$, suggesting similar performance in bilinguals and monolinguals.

Further to test the above null hypothesis in accuracy and reaction time data, Bayes factor analysis was administered using the Bayes Factor (BF) package in R (Morey, Rouder, & Jamil, 2014). Bayes factor is a comparison of how well the two hypotheses (null vs. alternative) predict the data with the relative evidence. For accuracy rate we obtained a BF value of 8.1 for no group and trial type interaction, suggesting positive evidence in favour of the null hypothesis (0.123). For mean correct RT and standard deviation correct RT, we obtained a BF value of 36.5 and 58.9 respectively for no group and trial type interaction, providing strong evidence in favour of the null hypothesis (0.027 & 0.016 respectively).

Linear Ballistic Accumulator (LBA) model. The dependent measures obtained from LBA model (Brown & Heathcote, 2008) are drift rate and response threshold. For drift rate, we performed 3 x 2 x 2 ANOVA with trial type (congruent, incongruent, neutral) and accumulator (true, false) as a within participant factors and group (bilingual, monolingual) as a between participant factor. The results indicated a main effect of trial type, F (2, 76) = 5.88, p < 0.005, suggesting larger drift rate on congruent trials relative to neutral trials and incompatible trials. The main effect of accumulator, F (1, 38) = 99.57, p < 0.001 was significant suggesting larger drift rate for true accumulator than the false accumulator. There was also a significant interaction between trial type and accumulator, F (2, 76) = 3.79, p < 0.05, indicating larger drift rate for true accumulator relative to false accumulator across all trial types. Interestingly, the significant main effect of group, F (1, 38) = 5.33, p < 0.05 indicated that the bilinguals had overall larger drift rate than the monolinguals. This evidence suggests that bilinguals had a faster evidence accumulation for a corresponding response choice than the monolinguals. There was also a marginal interaction between group and accumulator, F (1, 38) = 3.95, p = 0.053. The interaction between group and accumulator revealed a lower drift rate for monolinguals than bilinguals, particularly for the false accumulator (monolinguals=-2.018; bilinguals=-0.403) and; also slightly less for the true accumulator (monolinguals=1.66; bilinguals=2.46). This suggests that the monolinguals received relatively less evidence for decision processing in both false and true accumulator than bilinguals. No other interactions were significant for drift rate (Fs < 0.36). On the other hand, for response threshold, we performed 3 x 2 x 2 ANOVA, with response location (left, right) and stimulus location (left, right, neutral) as a within participant factors and group (bilingual, monolingual) as a between participant factor. The results revealed no significant main effect for response location, F (1, 38) = 0.064, p = 0.80, stimulus location, F (2, 76) = 0.621, p = 0.53, and group, F (1, 38) = 0.172, p = 0.68. However, there was a significant interaction between stimulus location and response location, F (2, 76) = 16.51, $p < 0.001$. No other interactions were significant (Fs < 1.75). On further analysis, the results revealed a lower response threshold for left response location compared to that of right response location for left visual field stimulus and; in contrast, the response threshold was lower for right response location relative to left response location for right visual field stimulus. This suggests that participants were less cautious to select the response when the stimulus location and response location were on the same side, than when they are on the opposite sides. No other comparisons were significant (ps >0.05).

In the button press paradigm, the results do not provide evidence for a bilingual advantage in terms of accuracy, and reaction time data. The results are consistent with the bilingual advantage literature in young adults, in which they reported no evidence for a bilingual advantage in the Simon task (Bialystok, Martin, & Viswanathan, 2005; Bialystok, et al., 2005; Bialystok, 2006; Salvatierra & Rosselli, 2010; Kousaie & Phillips, 2012; Gathercole, Thomas, Kennedy et al., 2014; Paap, Johnson, & Sawi, 2014). In contrast, for LBA model parameter estimates, in specific for drift rate, the results revealed larger drift rate for bilinguals suggesting faster decision processing relative to monolinguals. Thus, to pursue the possibility of a bilingual advantage further, we turned in Experiment 2 to the 'reach-to-touch' paradigm (Quek & Finkbeiner, 2013; 2014; Finkbeiner, Coltheart, & Coltheart, 2014; Ocampo & Finkbeiner, 2013; Finkbeiner & Heathcote, submitted). The goal of this next experiment was to investigate the time course of response activation along the direct and indirect stimulus-to-response routes in bilingual and monolingual young adults with the aim of better understanding how task-relevant and task-irrelevant information becomes activated and/or suppressed in bilingual and monolingual young adults in the Simon task.

Experiment 2: Reach-to-touch Paradigm

While a great deal of work has been done to establish the presence (or absence) of the so-called bilingual advantage in conflict-inducing tasks, and especially in the Simon task, the reason for the bilingual advantage in this particular task has not yet been established. Are bilinguals better at suppressing the task-irrelevant information? If so, this would suggest that bilinguals are better at controlling the response activation from the direct route which arises "automatically" or "involuntarily" from the spatial location information. Or is it that the bilinguals are better (faster?) at processing task-relevant information. This latter possibility would suggest that bilinguals are faster at activating the response activation from the cognitive route which is thought to be under the participants' control. In our second experiment we investigated the time course of response activation along these two independent routes in bilingual and monolingual young adults. Since it is difficult to distinguish whether response activation is produced along direct and indirect routes from button press measures (mean RT and accuracy data), a continuous behavioural measure was employed as it is better able to reveal when task-relevant and task-irrelevant information gains control of the overt response (Finkbeiner & Heathcote, submitted). One such continuous behavioural measure which meets these requirements is the 'reach-to-touch' paradigm (Spivey, Grosjean, & Knoblich, 2005; Song & Nakayama, 2009; Quek & Finkbeiner, 2013; 2014; Finkbeiner, Coltheart, & Coltheart, 2014).

In our version of the reach-to-touch paradigm, participants classified the color of the stimulus by reaching out and touching the appropriate response panel, fixed on either side of the computer monitor (Finkbeiner & Heathcote, submitted). An electromagnetic motion capture device was used to track the reaching responses, which allowed us to establish whether their initial movement was in the correct or incorrect direction. This was achieved by calculating x-velocity on each trial (Quek & Finkbeiner, 2013; Finkbeiner, Coltheart, & Coltheart, 2014), which is a signed value where positive values indicate reaching movements in the correct direction and negative values indicate reaching movements in the incorrect direction. Further, we combined the reach-to-touch paradigm with the response-signal procedure, in which participants were instructed to start their reaching movements in synchrony with an imperative go signal (cf. Finkbeiner, Coltheart, & Coltheart, 2014). The target stimulus and go signal were presented in three different stimulus-onset-asynchronies (SOA's): at 0ms, 150ms, and 250ms. In the latter two SOA's, the target stimulus was presented before the go signal. Across the 3 SOAs, we were able to elicit reaching movements across a wide range of stimulus viewing times. We refer to the time between stimulus onset and movement onset as the 'movement initiation time' (MIT). Finally, we analyse the initial x-velocity of each reaching response as a function of MIT. This allows us to determine how much the participant knew about the target stimulus (i.e., color) at the time of movement initiation, which allows us to map out the onset, growth and decay of the Simon effect in stimulus processing time.

Using the reach-to-touch paradigm in the Simon task, Finkbeiner & Heathcote (submitted) demonstrated how to disentangle response activation of the fast direct route from that of the slow cognitive route on incongruent and neutral trials respectively (see Fig. 2). On incongruent trials, the stimulus location and the response panel were on spatially opposite sides (Fig. 2A) and their findings showed that the stimulus location automatically elicited reaching movements in the incorrect direction (but only in movements with the earliest MITs). More specifically, for incongruent trials they found that the initial direction of movements initiated 100 ms following target onset were reliably incorrect (initial x-velocity was reliably negative). On neutral trials, the influence of stimulus location information was eliminated by presenting stimuli on the vertical axis (above and below central fixation) (Fig. 2B). In this condition, they demonstrated that the stimulus color information elicited reaching movements in the correct direction (but only in movements with the later MITs). In particular, for neutral trials they reported that the initial direction of movements initiated 240 ms following target onset were reliably correct (initial x-velocity was reliably positive). Thus, supporting dual-route claims, Finkbeiner & Heathcote (submitted) were able to differentiate the early emergence of response activation along the direct route for task-irrelevant stimulus information (i.e., location processing) from the later emergence of response activation on cognitive route for task-relevant stimulus information (i.e., color processing). In our second experiment we employed the same version of the 'reach-to-touch' paradigm to investigate possible differences between monolinguals and bilinguals in the time course of response activation from direct and indirect routes.

Method

Participants and test materials section were identical to those used in Experiment 1.

Procedure

In this version of the Simon task, participants were asked to reach out and touch the left response panel for red targets and the right response panel for green targets (or vice versa depending on the counterbalanced lists). The reaching movements for each trial were recorded using an electromagnetic motion capture system Polhemus Liberty (at 240Hz) from the sensor (weight: 3.69 grams) taped to the right index finger. Participants commenced each trial sequence by moving their right index finger to the "start position" located at the middle edge of the desk of width 140cm. The experiment began with two blocks of practice trials (n=80), and followed by eight blocks of experimental trials (n=320). In each trial, a central fixation cross was presented on screen for 500ms, followed by three beeps presented through headphones (Sennheiser, HD 280 Pro). The target color square was presented for 300ms in any one of the four locations (see Fig. 2). The final third beep served as imperative go signal, for which the participants were instructed to initiate their reaching movement. The auditory go signal and target stimulus were presented at three different SOAs: at 0ms SOA comprising 40% of the trials (target and go signal appeared simultaneously); at 150ms SOA comprising 40% of the trials (target appeared 150ms before the go signal) and at 250ms SOA (target appeared 250ms before the go signal). The purpose of using 3 different target-to-go signal SOAs was simply to elicit a wide range of movement initiation times (MITs), which is central to the analyses that we describe below.

On each trial, participants were required to initiate their responses within a 300ms response time window that opened 100ms before the go signal and closed 200ms after the go signal. However, if participants failed to initiate their movement within this response window (~450ms) the trial was terminated with a buzz and visual feedback was presented on screen (e.g. "Too Early!" or "Too Late!"). The reaching responses that were initiated before target onset were used to establish baseline information processing when no target information was presented. This is further supported in the data suggesting that the responses were on an average down the centre (see Figure 4) in the first MIT quantile, indicating that they were neither in the correct direction nor in the incorrect direction. Thus, the 'reach-to-touch' paradigm coupled with response signal procedure allowed us to track the reaching responses across a range of target viewing times, from ~100ms before target onset (at 0ms SOA) to ~450ms after target onset (at 250ms SOA). Further, participants were required to maintain a continuous forward reaching movement over the first ~250ms of response initiation and, if failed to maintain this criteria the trials were terminated with a buzz and visual feedback.

Data analysis

Practice trials in the initial two blocks were discarded from analysis as were trials in which participants failed to initiate their reaching movement within the response window. To track the time course of reaching responses as a function of stimulus viewing time in the Simon task, we followed similar protocol as described by Finkbeiner and colleagues to analyse reaching trajectories (see Finkbeiner et al., 2014; Finkbeiner & Heathcote, submitted). On each trial, first the x-velocity was calculated by filtering the position data with a two-way low pass Butterworth filter at 7Hz, and we calculated the derivatives (i.e., velocity and acceleration) through numerical differentiation. Then the movement onset and movement offset were measured by the tangential velocity profile, such that movement onset was defined as the first of 20 consecutive samples that exceeded 10cm/s, and movement offset was defined as the first of 20 consecutive samples that occurred after peak tangential velocity and that fell below 10cm/s. Further, to examine the effect of MITs on x-velocity, we ran a modified version of orthogonal polynomial trend analysis (OPTA; Woestenburg, Verbaten, Van Hees, & Slangen, 1983; Karayanidis, Provost, Brown, Paton, & Heathcote, 2011) on x-velocity profiles. In this analysis, each trial was ranked according to the MIT latency and then the MIT ranks were included as a covariate in a polynomial regression model of participants' x-velocity profiles (for a detailed description of this analysis, see Finkbeiner et al., 2014; Quek & Finkbeiner, 2013; 2014). The regression coefficients were then used to generate predicted x-velocity values for each trial, allowing for a very fine grained analysis of changes in the reaching response as a function of target viewing time. Only the initial portion of the reaching trajectory i.e., 150ms was analysed to note the time course of experimental effects across trials. This in turn helps to capture the amount of information accumulated about the target stimulus at the time of movement initiation. We refer to this dependent measure as initial x-velocity. For statistical analysis, we computed the initial x-velocity by averaging across the first 150ms of the predicted x-velocity profiles and then entered these mean values into a linear mixed effect model (LMM; Bates, 2005), with subject as a random effect and MIT percentile as a fixed effect. As mentioned earlier, the movement initiation times obtained across the three different SOA's were rank ordered and then grouped into 20 quantiles of equal proportion such that the 1st quantile consisted of the trials with the fastest MITs and the 2nd quantile consisted of second fastest MITs and so on. The distribution of movement initiation times (MITs) is depicted in Figure 3A. This broad distribution of MITs is important as it allows us to examine the evolution of correct (and incorrect) responses across the first few hundred milliseconds of stimulus processing time. Figure 3B illustrates the mean predicted x-velocity profiles across 20 MIT quantiles on incongruent trials for bilinguals and monolinguals. As this figure makes clear, the longer the participants waited to begin their reaching movements, the better they knew how to respond as indicated by their reaching peak x-velocity in the correct direction more quickly.

Statistical analyses

The data was analysed with a linear mixed-effect model (LMM) (Bates, 2005; Baayen, Davidson, & Bates, 2008) implemented in R with the lmer4 package (Bates, Maechler, & Bolker, 2012). This analysis allowed us to simultaneously consider both fixed and random effects in detail and evaluate the contribution of each term to the model by comparing that model with one that excluded the effect under inspection. In each case, the test values (AIC, BIC, log likelihood) were used to indicate which model should be preferred. These values provided a measure of goodness-of-fit, penalising them for the number of free parameters to prevent over-fitting. Our incremental model comparison procedure resulted in a model that included Subject as a random effect, together with fixed effects trial type (congruent, incongruent, neutral), and group (monolingual, bilingual) for accuracy data and including MIT quantile (1 to 20) for reaching data. We further report coefficients (b), standard errors (SE), and t-values for the resulting model selected. As is typical in LMM analyses, we have taken a co-efficient magnitude of at least twice its standard error (i.e. $|t|>2$) as our criterion for significance (Baayen, Davidson, & Bates, 2008). The coefficients for the trial type and group factor used the congruent trial and bilingual group as a baseline respectively, so that the negative values indicate smaller x-velocities relative to the congruent trial and bilingual group in reaching data.

Results

The dependent measures in this paradigm were accuracy (%) and initial x-velocity by Movement Initiation Time (ms).

Accuracy. The accuracy rates were very high in all the three trial types, which is presumed to be due to the relatively long duration of the reaching response, which provides participants an opportunity to recognize and correct mistakes they may have made at the beginning of their movement. The LMM analysis revealed a significant main effect of trial type, indicating higher accuracy rates on congruent trials (*M* = 99.84, *SD* = 0.58) relative to incongruent trials (*M* = 99.27, *SD = 1.48)*, *b* = -1.7, *SE* = 0.54, *z* = -3.15. There was no significant difference between congruent and neutral trials (*M* = 99.85, *SD = 0.31)*, *b* = -0.11, *SE* = 0.60, *z* = -0.19. In contrast, including group as a factor did not significantly improve the fit of the model, nor did the interaction between trial type and group (*p's*>0.05).

Initial x-velocity profile. The results revealed a significant main effect of trial type suggesting higher initial x-velocity on congruent trials relative to neutral trials (b = -5.19, SE = 0.39, t = -13.25) and incongruent trials (b = -14.67, SE = 0.45, t = -32.32). There was no significant main effect of group, $\chi(1) = 0.85$, *p=0.35*. Further, there was also a significant increase in x-velocity across MIT quantiles (b = 928.67, SE = 35.24, t = 26.35). In addition to these main effects, there was an interaction between MIT quantile and trial type, which suggests higher x-velocity on compatible trials across MIT quantiles relative to neutral trials (b = -125.75, SE

= 43.31, t = -2.90) and incongruent trials (b = -702.57, SE = 50.19, t = -14). Interestingly, there was also an interaction between trial type and group, which suggests lower x-velocity for neutral trials (b = -4.66, SE = 0.55, t = -8.37) and incongruent trials (b = -10.17, SE = 0.64, t = -15.76) relative to compatible trials for monolinguals than bilinguals. The interaction between group and MIT quantile indicates that the x-velocity was lower for bilinguals relative to monolinguals across MIT quantiles (b = 297.66, SE = 50.31, t = 5.92). There was, however, a significant three-way interaction between MIT quantile, trial type and group on incongruent trials (b = -221.65, SE = 71.39, t = -3.10) and neutral trials (b = -134.13, SE = 61.69, t = -2.17).

To further examine the nature of the three-way interaction, we analysed each group separately using LMM as described earlier. Table 4 presents the coefficients, standard errors (SE's) and t-values for bilingual and monolingual groups presented in the final model. As mentioned earlier, the coefficient value twice the size of the SE was taken as significant (|t|>2). Across both the groups, the initial x-velocity was significantly higher for congruent trials than the incongruent and neutral trials. There was also a significant increase in initial x-velocity with MIT quantiles in both the groups. Further, an interaction between trial type and MIT quantile suggested that the initial x-velocity significantly changed across quantiles between trial types in both the groups. This two-way interaction is illustrated in Figure 4, the zero intercept on the y-axis indicates a net x-velocity of 0 (cm/sec). The initial x-velocity values greater than *zero* correspond to initial reaching movements in the correct direction; values less than *zero* indicate initial reaching movements in the incorrect direction. The mean MIT in the first MIT quantile is negative, indicating that participants' earliest responses were initiated before the target appeared. The reaching movements initiated within the first ~100ms of stimulus viewing time (i.e., the first five MIT quantiles) were on the zero line. This demonstrates that the initial reaching movements were neither in the correct nor incorrect direction. However, the reaching movements that were initiated after ~100ms of stimulus viewing time differ as a function of trial type. On congruent trials, the reaching movements were in the correct direction; in contrast, on incongruent trials, the pattern was bimodal. Initially the reaching movements were in the incorrect direction at earliest stimulus processing stage and then with a further increase in the stimulus viewing time the reaching responses were in the correct direction. On neutral trials the initial x-velocity of movements was not different from zero until after ~240ms of stimulus viewing time. From that time on, the initial x-velocities steadily increased in the correct direction.

Using pairwise comparisons to look at the time course of the Simon effect in bilinguals and monolinguals

In our first pairwise comparison, we investigated when in stimulus processing time the difference emerged between congruent and incongruent trials i.e., onset of the Simon effect, and when in stimulus processing time the difference resolved i.e., decay of the Simon effect. To test this we contrasted initial x-velocities across congruent and incongruent trials at each of the 20 MIT quantiles using paired t-test with Bonferroni corrected p values separately across groups. The results revealed that for bilinguals the difference emerged from the 6th MIT quantile at 106ms of stimulus viewing time ($p < 0.05$) and was resolved by the 18th quantile at 299ms of stimulus viewing time ($p = 0.28$). This pattern was identical in the monolinguals, where the difference emerged from the 6th quantile at 110ms of stimulus viewing time ($p < 0.01$) and resolved by the 18th MIT quantile at 289ms of stimulus viewing time ($p = 0.08$). The data suggested similar time window of onset and decay of the Simon effect across bilingual and monolingual young adults.

Using pairwise comparisons to look at the time course of the trial type (congruent, neutral, incongruent) in bilinguals and monolinguals

In our second set of comparisons, we investigated the point in stimulus viewing time when the initial x-velocity profiles of each trial type (congruent, neutral, and incongruent) differed from the zero horizontal line (Fig. 4). To do this, we ran one sample t-tests with Bonferroni corrected p values at each of the 20 MIT quantiles across trial type within each language group.

Congruent Trials. On congruent trials (Fig. 4), the initial x-velocities of our bilingual participants were significantly greater than zero for movements that commenced from the 7th MIT quantile at 127ms ($p < 0.05$) until the 20th MIT quantile at 354ms ($p < 0.01$) and in monolinguals it was from the 8th MIT quantile at 153ms ($p < 0.05$) till 20th MIT quantile at 340ms. The time points across groups indicates that on congruent trials the bilingual participants produced reliably correct initial movements earlier in time than the monolingual participants (by 26ms).

Neutral Trials. On neutral trials (Fig. 4), the initial x-velocities for the bilingual participants were significantly greater than zero for movements commenced from the 13th MIT quantile at 230ms ($p < 0.05$) until the 20th MIT quantile at 365ms ($p < 0.001$), whereas for monolingual group the initial x-velocities were significantly greater than zero for movements that commenced from the 16th MIT quantile at 263ms ($p < 0.05$) until 20th MIT quantile at 352ms ($p < 0.001$). The data points suggest that on neutral trials, the bilinguals produced reliably correct initial movements earlier in time than the monolinguals (by 33ms).

Incongruent Trials. On incongruent trials, as mentioned earlier the pattern was bimodal, the initial x-velocities were significantly different at two stages along the zero (Fig. 4). First stage, the initial x-velocities were significantly less than zero, at the earliest stimulus processing time (~150ms), indicates the reaching movements in the incorrect direction i.e., towards the wrong response panel. For bilingual group, the initial x-velocities were significantly less than zero for movements that commenced from the 8th MIT quantile through to the 11th MIT quantile (~151ms through to 198ms; $p < 0.05$), whereas for the monolingual group, it was from the 6th MIT quantile through to the 9th MIT quantile (~108ms through to 168ms; $p < 0.05$). The time course differences between groups at this early stage suggest that the bilingual participants took longer stimulus viewing time to produce initial movements in the incorrect direction relative to monolinguals (by 43ms). Second stage, the initial x-velocities were reliably greater than zero, at the later stimulus processing time (~350ms), illustrates the reaching movements in the correct direction i.e., towards the correct response panel. For the bilingual group, the later stage was not yet observed significantly until the 20th MIT quantile at 351ms ($p = 0.22$), whereas for the monolingual group, it was just observed at the 20th MIT quantile at 344ms ($p < 0.05$). The data at the later stage indicates that monolinguals' initial x-velocities were reliably above chance in the correct direction relative to bilinguals' initial x-velocities.

This fine grained analysis reveals when in stimulus viewing time the reaching responses were significantly different from zero, and thus helps to distinguish response activation differences from the direct and indirect routes. To summarize, on neutral trials, the time point when the initial x-velocity was significantly greater than zero indicates the response activation from the indirect "cognitive" route for task-relevant information i.e., color processing. The group data shows that the bilinguals are faster to activate task-relevant information compared to monolinguals. Further, on incongruent trials, the time point when the initial x-velocity was reliably below zero in the incorrect direction represents the point in time when the activation of task-irrelevant location information gains control of the response formulation process. The group data shows that bilinguals took longer to activate responses along the direct route than monolinguals. Interestingly, when looking at the time course of the Simon effect itself (through pairwise comparisons of congruent and incongruent trials), there were no differences between groups.

Discussion

The purpose of the present study was two-fold. First, to investigate the decision processing mechanism (experiment 1) by fitting accuracy and reaction time data to the LBA model (Brown & Heathcote, 2008). Similar to previous studies, the results of button press measures (mean accuracy and mean reaction time) suggested similar performance between bilingual and monolingual young adults (Bialystok, Martin & Viswanathan, 2005; Bialystok, et al., 2005; Bialystok, 2006; Salvatierra & Rosselli, 2010; Kousaie & Phillips, 2012; Gathercole, Thomas, Kennedy et al., 2014; Paap, Johnson & Sawi, 2014). In contrast, the modelling data revealed decision processing differences between language groups in the Simon task. In which bilinguals had larger drift rate suggesting faster evidence accumulation for response execution relative to monolinguals. The second aim was to investigate the effect of bilingualism on the temporal dynamics of cognitive control (experiment 2). In particular, we sought to determine whether the bilinguals are better than monolinguals at controlling the activation of task-irrelevant information along the direct route, or at activating task-relevant information from the indirect route, or both. To investigate this, we combined the 'reach-to-touch' paradigm with the response-signal procedure in the Simon task (Finkbeiner & Heathcote, submitted), in which participants reaching responses were initiated across a wide range of stimulus viewing times. This fine grained analysis allowed us to reveal the temporal dynamics of response activation from the direct and cognitive routes in the Simon task. The results of the 'reach-to-touch' paradigm illustrated that the bilinguals suppress task-irrelevant information for a longer period of time and that they activate task-relevant information sooner.

The reaching trajectories across trial types (i.e., congruent, neutral and incongruent) are consistent with the findings reported by Finkbeiner & Heathcote (submitted). On congruent trials, the reaching responses were in the correct direction at earliest stimulus viewing time (~127ms for bilinguals; ~153ms for monolinguals). These findings are similar to traditional button press measures (reaction time) in the Simon task, in which the reaction time is faster on congruent trials relative to neutral trials and incongruent trials (Simon & Rudell, 1967; Acosta & Simon, 1976; Umilta, Rubichi, & Nicoletti, 1999; De Jong et al., 1994; Lu & Proctor, 1995; Wiegand & Wascher, 2005). However, the reaching responses on these trials are ambiguous with respect to isolating whether response activation stems from the direct route or cognitive route. On incongruent trials the reaching responses were bimodal. First, in the incorrect direction towards wrong response panel at the earliest stimulus viewing time (at ~151ms for bilinguals; at ~108ms for monolinguals) and second, in the correct direction towards the correct response panel at the later stimulus viewing time (no significant difference for bilinguals; at ~344ms for monolinguals). The only information that is driving the reaching responses in the incorrect direction on incongruent trials is the response activation from the task-irrelevant (spatial) information (Buetti & Kerzel, 2009). And, on neutral trials the reaching responses emerged significantly in the correct direction at longer stimulus viewing time (at ~230ms for bilinguals; at ~263ms for monolinguals). The only information that is driving the reaching responses in the correct direction on neutral trials is the response activation purely from the task-relevant (color) information.

These observations are consistent with the dual-route accounts of the Simon effect (De Jong, Liang, & Lauber, 1994; Kornblum et al., 1990; Wiegand & Washer, 2005; Ridderinkhof, 2002), which assumes that the stimulus' location automatically activates its corresponding response along a very fast direct route (e.g., right side stimulus activates right-hand response). In the present study, we captured the direct route activation on incongruent trials, in which the reaching responses were in the incorrect direction towards stimulus location at early stimulus viewing times (Buetti & Kerzel, 2008; 2009; Finkbeiner & Heathcote, submitted). And later as the stimulus viewing time increased, the interference of spatial information was resolved completely. In contrast to the direct route which processes stimulus location, the task-relevant (color) information is said to be processed along the slower, cognitive route. Using neutral trials, we were able to observe the time course of response activation along this cognitive route. Because the neutral stimuli were presented along the vertical meridian, the spatial location of these stimuli was orthogonal to the response locations, thereby minimizing location-based interference. Consistent with the dual-route accounts, participants needed to view a neutral stimulus for a longer period of time before they were able to produce a reliably correct initial movement. In the next section, we further focus on the reaching trajectories of incongruent and neutral trials between bilingual and monolingual participants, as they explicitly represent the response activation from the direct and cognitive routes respectively.

Are bilinguals faster at activating task-relevant information from the *cognitive route*? As discussed, the reaching responses on neutral trials represented the response activation from the cognitive route (i.e., controlled route). The results between groups revealed that the bilinguals required shorter stimulus viewing time to plan their reaching responses in the correct direction relative to monolinguals. The faster response execution in bilinguals (by 32ms) suggested earlier response activation from the cognitive route for task-relevant color information. Are bilinguals better at controlling the activation of task-irrelevant information along the *direct route*? As indicated, reaching responses in the incorrect direction on incongruent trials represent the response activation from the direct route (i.e., automatic route). In this condition, the results showed that the bilinguals required longer stimulus viewing time to initiate movements that travelled in the incorrect direction than monolinguals. Thus, the later emergence of task-irrelevant information in bilinguals (by 43ms) may suggest that they are better at controlling the response activation from the automatic route for task-irrelevant spatial information. However, while bilinguals took longer to begin producing initial movements in the incorrect direction at earliest stimulus viewing time, it should be noted that the reaching responses that were initiated at the later stimulus viewing time were never in the correct direction for the time window that we used in this study (~350ms). Thus, while bilinguals appear to be better at resisting capture initially by task-irrelevant information, they require more stimulus viewing time to isolate the task-relevant information in incompatible stimuli and to formulate an appropriate response.

To our knowledge, none of the previous studies exclusively investigated the time course of response activation from direct and cognitive routes in bilingual and monolingual participants in the Simon task. In this study we reported that monolinguals and bilinguals activated task-relevant and task-irrelevant information along the direct and indirect routes differently. Firstly, bilinguals identified the task-relevant color information at shorter stimulus viewing time relative to monolinguals in the neutral trials which suggested that they are faster at engaging response activation from the cognitive route. Secondly, bilinguals took longer to be captured by the task-irrelevant spatial information in the incongruent condition, which indicated that they adopted a more cautious strategy in our paradigm. One possibility is that bilinguals were better at selectively suppressing activation along the direct route (Ridderinkhof, 2002), which would account for the longer stimulus viewing times relative to monolinguals. But it is difficult to reconcile this possibility with the finding that bilinguals reaching responses were never in the correct direction at later stimulus viewing time on incongruent condition for the time window selected in the present study (~350ms). In fact, while the overall pattern of initial movements was similar across groups, the bilinguals never did recover in the incongruent condition and produce initial movements that were reliably correct. The results from the reach-to-touch paradigm are further supported by LBA model drift rate data, in which the bilinguals had larger drift rate relative to monolinguals. This data suggests that bilinguals had accumulated more evidence for the response choice, which in turn might correspond to faster responses for task-relevant information than monolinguals.

The current study data sheds new light on the temporal dynamics of cognitive control in bilinguals and monolinguals for the Simon task. Using the reach-to-touch paradigm, we were able to track the time course of response selection from the direct and cognitive routes over stimulus processing time. This in turn helped us to reveal when exactly the bilingual and monolingual groups engaged response activation from direct and cognitive routes. While our results indicate that bilinguals were faster to activate task-relevant information and better at controlling task-irrelevant information, this did not translate into a smaller Simon effect. In fact, when quantifying the magnitude of the Simon effect, we found no difference between our monolingual and bilingual groups. If anything, our findings suggest that, once captured by the task-irrelevant spatial information, our bilingual participants found it more difficult than our monolingual participants to recover and activate task-relevant stimulus information.

The same set of language groups matched across age, years of formal education, handedness, non-verbal intelligence, video game playing, and parental education level, completed both the button press and the reach-to-touch version of the Simon task. However, group differences were picked up only in the reaching responses. One possible explanation for this contrast may be due to the differences between the response time window captured in the button press and reach-to-touch paradigm measures. The button press measures such as mean RT data represents the end point of cognitive decision making (~500ms), which is an amalgamation of multiple processes (perception, cognitive process, motor preparation, motor execution). Due to this poor temporal resolution with button press measures, it might be insensitive to capture the subtle group differences in the Simon task. Whereas the ‘reach to touch’ paradigm coupled with the response signal procedure (Finkbeiner et al., 2014) are designed to capture the interactive nature of the cognitive process and the motor response in the Simon task as it unfolds over time at an early stimulus processing stage (~250 ms). Thus the reaching trajectories are much more sensitive and dynamic than mean RT’s, (which range from ‘fast’ to ‘slow’ in a single positive direction) to record subtle group differences (Finkbeiner et al., 2014). Moreover, in previous studies when there was no difference between monolingual and bilingual young adults in the button press paradigm, high temporal measures such as ERP's, were capable of detecting processing differences between bilingual and monolingual participants (Kousaie & Phillips, 2012; Fernandez, Tartar, Padron, & Acosta, 2013; Sullivan, Janus, Moreno, Astheimer, & Bialystok, 2014; Coderre & van Heuven, 2014; Heidlmayr, Hemforth, Moutier, & Isel, 2015). These findings suggest that the high temporal measures are sensitive enough to detect subtle processing differences between groups, which were not captured in the button press measures.

In conclusion, the present study has documented differences in the temporal dynamics of cognitive control between bilinguals and monolinguals in the Simon task using a reach-to-touch paradigm. The data is suggestive of a more efficient and dynamic attentional control system in bilinguals relative to monolinguals, as indicated by faster activation of task-relevant stimulus information in the neutral condition and a delay in the activation of task-irrelevant stimulus information in the incongruent condition. Nevertheless, not even the fine-grained analysis afforded by the reach-to-touch paradigm was able to reveal a bilingual advantage in the form of a smaller Simon effect or in the time course of conflict resolution.

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Tables & Figures

Table 1: Demographic information for participant groups.

Variables	Monolinguals Mean (SD)	Bilinguals Mean (SD)	Sig.
Age (in years)	21.20 (4.78)	20.65 (3.58)	$p = 0.683$
Formal Education (in years)	13.85 (2.10)	15.30 (3.18)	$p = 0.098$
Edinburgh's Handedness Scores	83.69 (15.29)	88.69 (17.31)	$p = 0.338$
Ravens Score's	10.55 (1.23)	10.60 (0.88)	$p = 0.338$
Video Game Playing (Playing hrs/week)	1.45 (2.32)	1.05 (1.93)	$p = 0.557$
Average Parental Education (5 point rating scale)	3.45 (1.39)	3.60 (1.53)	$p = 0.338$
Computer Usage (hrs/day)	4.85 (2.32)	6.60 (2.90)	$p < 0.05$
	English	***English***	***Non-English***
Age of Acquisition (in years)	0.45 (0.68)	3.00 (2.02)	1.57 (1.46)
Language Usage (in %)	100	64.25 (9.49)	29.9 (12.06)
Proficiency Rating (10 point scale)			
Speaking	9.85 (0.48)	9.10 (1.07)	8.40 (0.94)
Understanding	9.80 (0.41)	9.15 (1.08)	8.95 (0.88)
Reading	9.75 (0.55)	9.10 (1.16)	7.55 (1.87)

Table 2: Mean accuracy rate and standard deviation (SD) across trial type in bilingual and monolingual participants for button press version of the Simon task.

Trial Type	**Mean Accuracy Rate (SD)**	
	Bilinguals	**Monolinguals**
Congruent Trial	96.29 (18.89)	96.98 (17.09)
Incongruent Trial	86.71 (33.95)	89.90 (30.12)
Neutral Trial	95.04 (21.71)	95.16 (21.71)

Table 3: Mean Reaction time (RT) and standard deviation (SD) across trial types in bilingual and monolingual participants for button press version of the Simon task.

Trial Type	**Mean RT (SD)**	
	Bilinguals	**Monolinguals**
Congruent Trial	500.73 (103.43)	505.72 (120.93)
Incongruent Trial	549.84 (100.54)	551.54 (118.57)
Neutral Trial	524.51 (97.86)	522.56 (113.82)

Table 4: Fixed effects across groups estimated with LMM.

Group	**Fixed effects**	**b**	**SE**	**t-value**
Bilingual	Trial type (Incongruent)	-14.73	0.34	-42.70
	Trial type (Neutral)	-5.26	0.29	-17.68
	MIT quantile	671.51	19.01	35.32
	Trial Type* MIT quantile (Incongruent)	-460.10	27.07	-16.99
	Trial Type* MIT quantile (Neutral)	-88.22	23.36	3.78
Monolingual	Trial type (Incongruent)	-24.53	0.53	-45.63
	Trial type (Neutral)	-9.66	0.46	-20.78
	MIT quantile	868.24	29.62	29.31
	Trial Type* MIT quantile (Incongruent)	-599.71	41.89	-14.32
	Trial Type* MIT quantile (Neutral)	-175.45	36.23	4.84

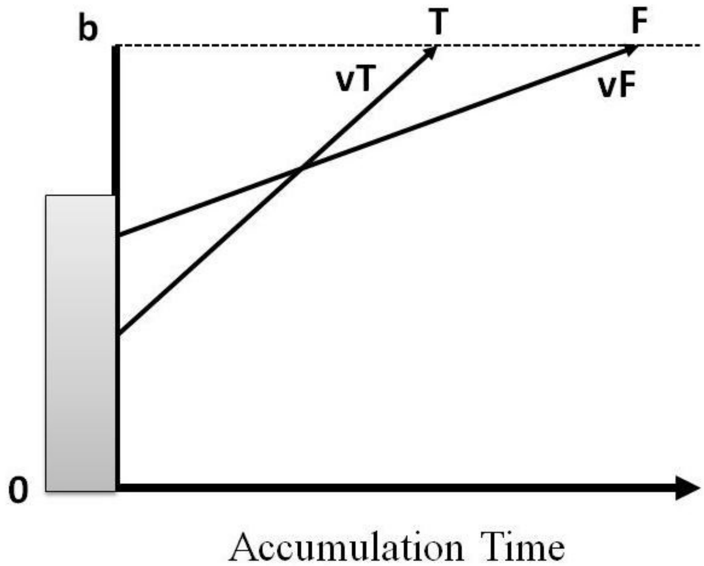

Figure 1: Linear Ballistic Accumulator model (b=response threshold; vT=drift rate for true accumulator; vF=drift rate for false accumulator). The shaded rectangle represents the start point variation from trial to trial.

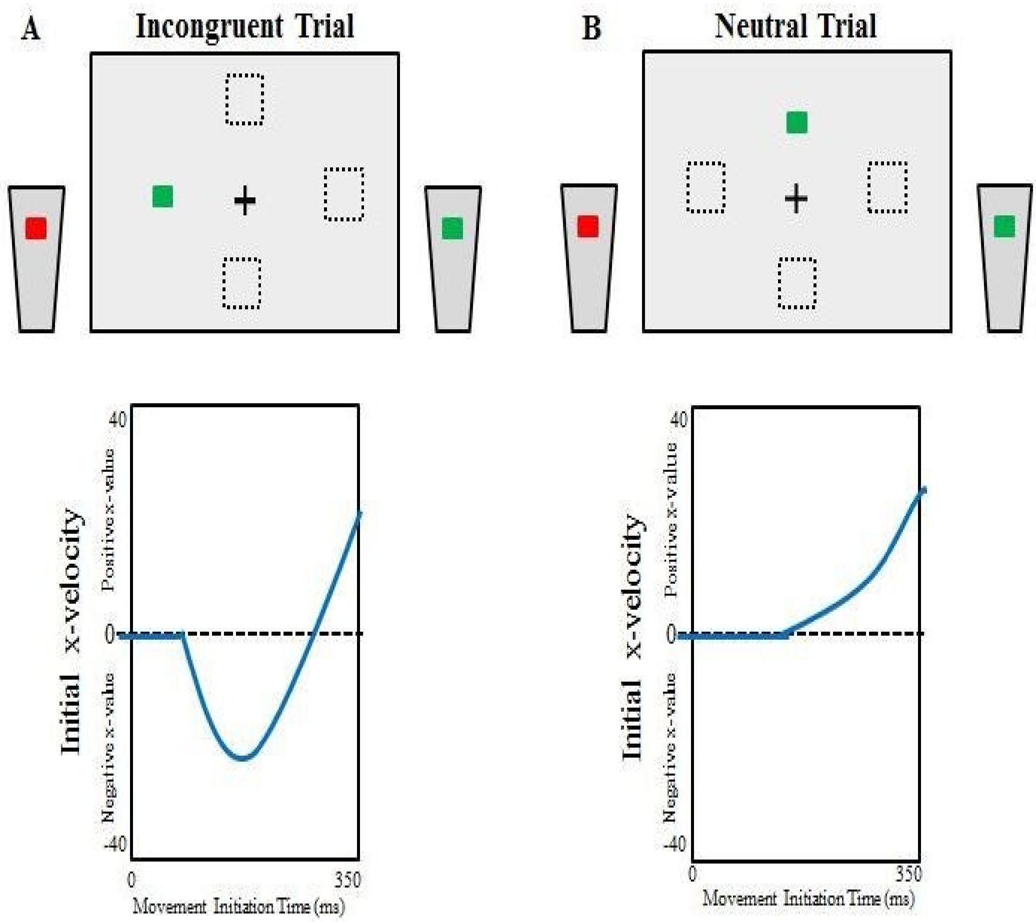

Figure 2: Representation of initial x-velocity as a function of movement initiation time for (A) incongruent trials and (B) neutral trials in Finkbeiner & Heathcote (submitted) study. The initial x-velocity is the average of first 150ms of the reaching responses. The *zero* on y-axis corresponds to x-velocity of zero. The reaching responses above *zero* indicate positive x-values in the correct direction and reaching responses below *zero* indicates negative x-values in the incorrect direction. On incongruent trial (A), at early movement initiation time points the initial x-velocity was negative in the incorrect direction. On neutral trials (B), at later movement initiation time points the initial x-velocity was positive in the correct direction. The dotted square inside the screen represents the other three locations of stimuli presentation. The panels on either side of the screen are the response target locations for the corresponding target color.

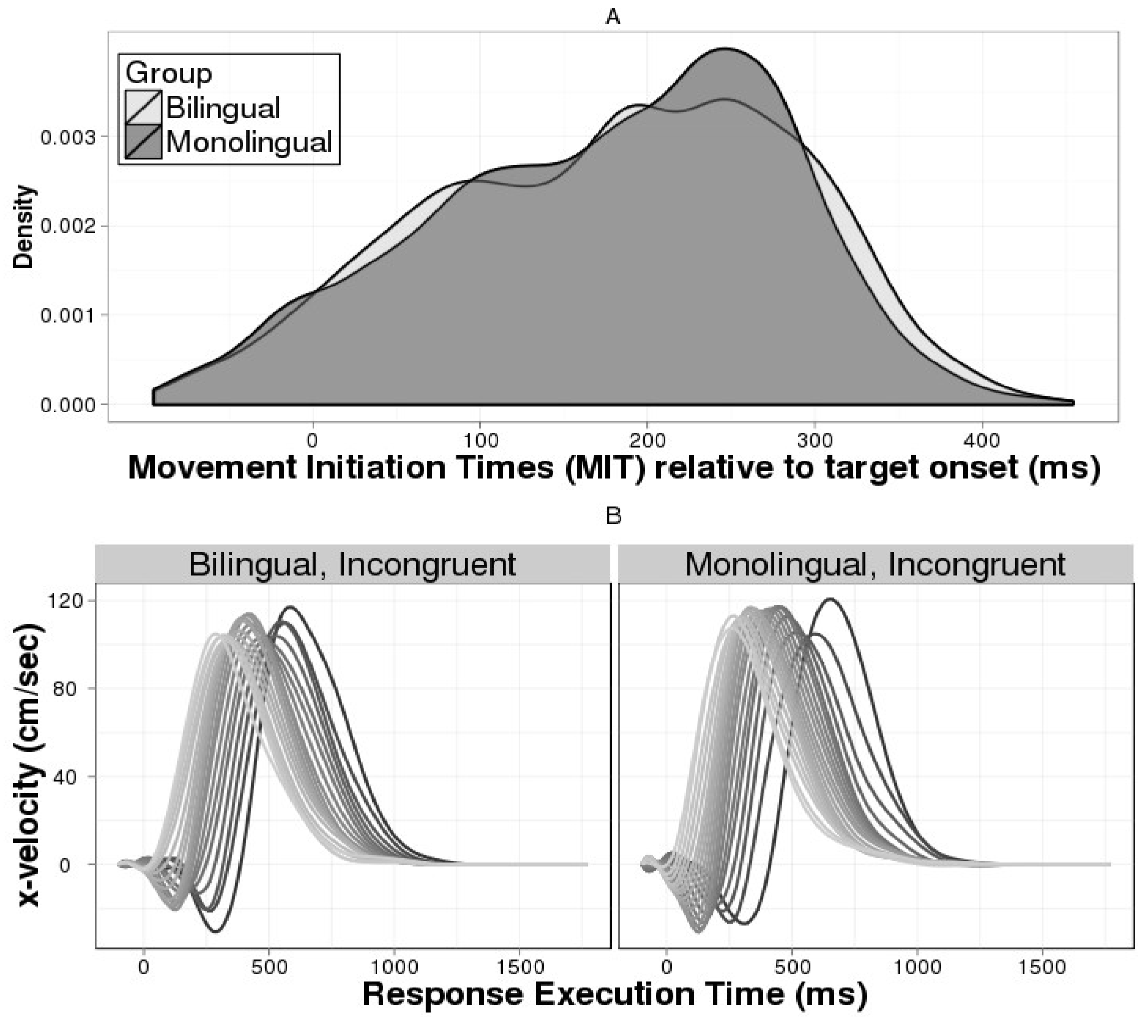

Figure 3: (A). Distribution of Movement Initiation Time's (MIT's) from -100ms (before target onset at 0ms SOA) to 450ms (after target onset at 250ms SOA) for bilinguals (light grey shaded area) and monolinguals (dark grey shaded area). (B). Reaching movements across 20 quantiles on incongruent trials for bilinguals (left-side panel) and monolinguals (right-side panel). Each quantile consisted of 5% of total trials arranged in ranking order, the first quantile consisted of first fastest MITs, and second quantile consisted of next fastest MITs and so on. The darkest lines correspond to reaching responses initiated in the earlier MITs and greyest lines correspond to reaching responses in the longer MITs. The longer that participants view the target stimulus before response initiation, faster the emergence of peak x-velocity in the correct direction.

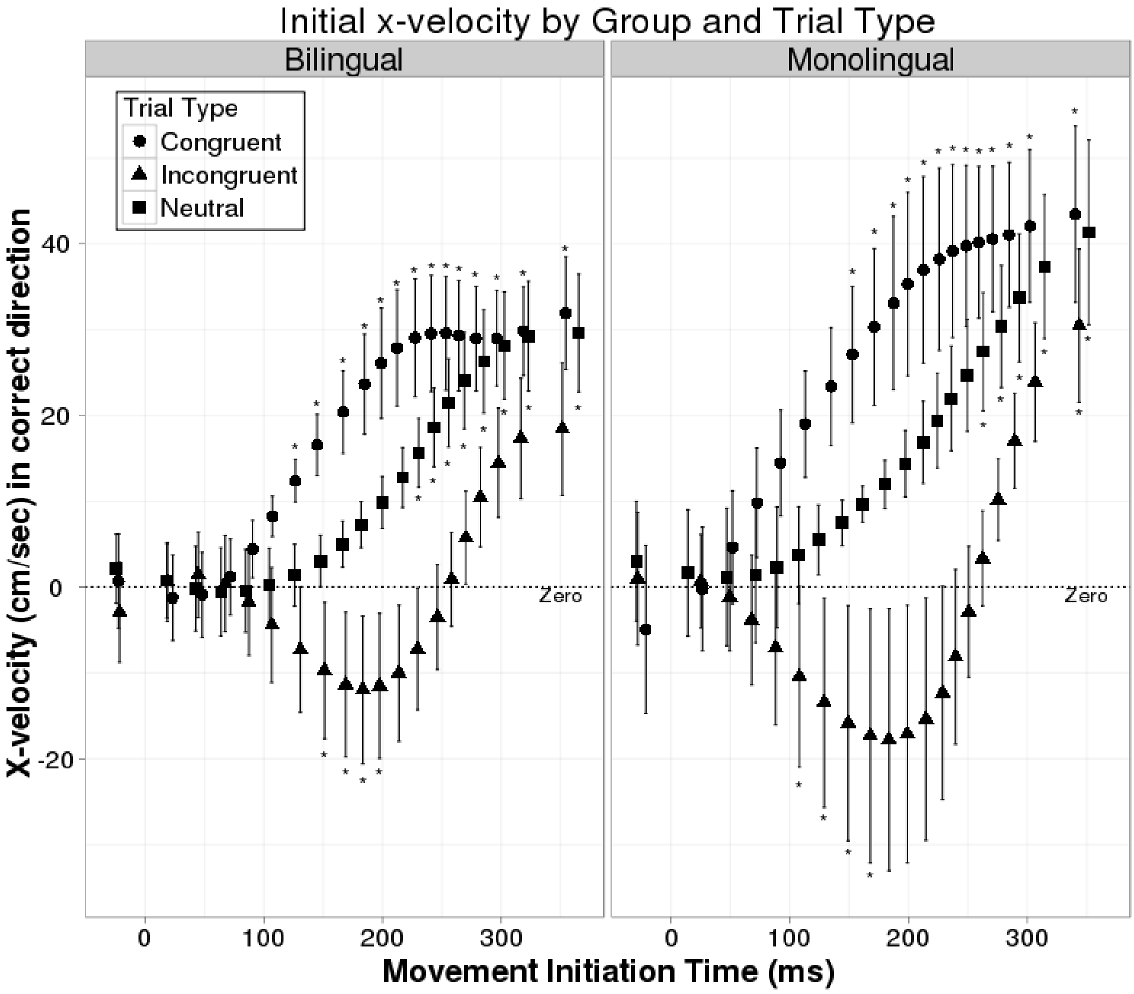

Figure 4: Initial x-velocity as a function of Movement Initiation Time (MIT) for congruent, incongruent and neutral trial types. Error bars represent confidence intervals. The *zero* on y-axis corresponds to x-velocity of zero. The reaching responses above *zero* indicate positive x-values in the correct direction and reaching responses below *zero* indicates negative x-values in the incorrect direction. The reaching profiles vary as a function of trial type after ~100ms of target viewing time. Asterisks indicate Bonferroni corrected ($p<0.05$) significant difference between *zero* and x-velocity across trial types.